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INTEGRATING COMPUTATIONAL BIOMECHANICS AND ULTRASOUND SIMULATIONS TO IMPROVE ULTRASONIC VISUALIZATION AND QUANTIFICATION OF ARTERIAL MECHANICS

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SUMMARY

Vascular imaging with ultrasound still shows severe limitations and further development of new imaging and signal-processing techniques is required. Since in-vitro or in-vivo setups do not offer sufficiently accurate information on the actually imaged blood vessel behavior, there is a need for a simulation tool where synthetic ultrasound (US) images can be validated towards a ground truth. We developed a simulation environment integrating computational biomechanics and US-simulations. First, CFD was coupled with US-simulations, which allowed to model US-images resulting from complex flow fields. This method is however limited by the absence of the moving vessel wall and therefore, we expanded the multiphysics tool by integrating fluid-structure interaction simulations with the US-simulator. An overview of the methodology to couple these different simulation strategies is given. The potential of these multiphysics simulations is demonstrated with the investigation of color flow imaging in a rigid and flexible blood vessel model.

Key Words: *CFD, FSI, ultrasound simulations, carotid artery.*

1 INTRODUCTION

In the context of early detection of cardiovascular diseases, ultrasonic imaging is often applied in clinical practice due to its non-invasive and radiation-free nature. Although today's ultrasound scanners are the result of numerous advances in several research areas, still many of the imaging goals are not fully achieved. Of note, vascular imaging shows several limitations: (i) only 1D blood flow measurements can be performed, visualizing the velocity component along the scanline, (ii) assessment of mechanical properties of arteries and plaques has only been investigated to a limited extent, with arterial distension estimation the most successful application so far. Hence, improved imaging and post-processing methods are needed.

2 METHODS AND APPLICATIONS

2.1 Overall modeling approach

Imaging development requires proper testing and validation, nowadays based on in-vitro and in-vivo setups. However, these do not allow proper validation of ultrasound (US) images, since the imaged flow field and/or vessel wall deformation is not known and, other measurement techniques, also prone to errors, are necessary to reveal the true blood vessel behavior behind the US-image. A simulation environment which creates synthetic US-images from fully known hemodynamics and vessel wall mechanics would therefore be highly useful. An important tool in this context is Field II [1]. This software allows to model any linear imaging setup with advanced transducer geometries, scan sequencing and beam formation. The backscattered radiofrequent (RF) signals are obtained by modeling tissue as a distribution of point scatterers on which US-waves reflect. Hence, realistic US-images of arbitrary vessel behavior can be simulated, by moving the scatterers during the simulated scan according to realistic blood velocities and structural displacements. The total scatterer number is related to the imaging resolution and the scattering strength is modeled using a normal distribution of scattering amplitudes with mean and standard deviation adapted to the tissue properties.

However, because of the complex arterial geometries and vascular material properties, the scatterer movement cannot be obtained through analytical solution of the equations governing the blood flow and vascular wall behavior. Complex numerical techniques are required for this purpose. In a first phase, we studied ultrasonic blood flow imaging methods in a carotid artery, by deriving blood velocities from computational fluid dynamics (CFD) and using them as an input to Field II [2]. A realistic 3D vascular geometry and mesh was reconstructed from medical scans with the software Mimics (Materialise, Leuven, Belgium) and the CFD-problem was solved with Fluent 6.2 (Fluent Inc., Sheffield, UK).

This simulation strategy is however limited by the absence of the vessel wall. Therefore, we extended the computational phantom to allow for the simulation of the integral blood vessel behavior, by moving scatterers according to blood velocities and mechanical deformations obtained from fluid-structure interaction (FSI) simulations. FSI-modeling allows to simultaneously solve the blood flow and vessel wall deformation problem, by taking into account their mutual influence [3]. We used a partitioned FSI-approach, computing the flow and structural equations with a separate flow and structural solver. An in-house code 'Tango' was used to couple the flow solver Fluent and the structural solver Abaqus (Simulia, Inc., Providence, RI, USA). In particular, Dirichlet-Neumann partitioning was used (flow problem is solved for a given displacement; structural problem is solved for a stress boundary condition applied on wet side of the structure). To enhance convergence of the coupling, an Interface Quasi-Newton method was used, which replaces the complex fluid or solid solver on the interface by approaching the Jacobian of the solver on the interface [4]. For a complete overview on the applied methodology, we refer to fig. 1.

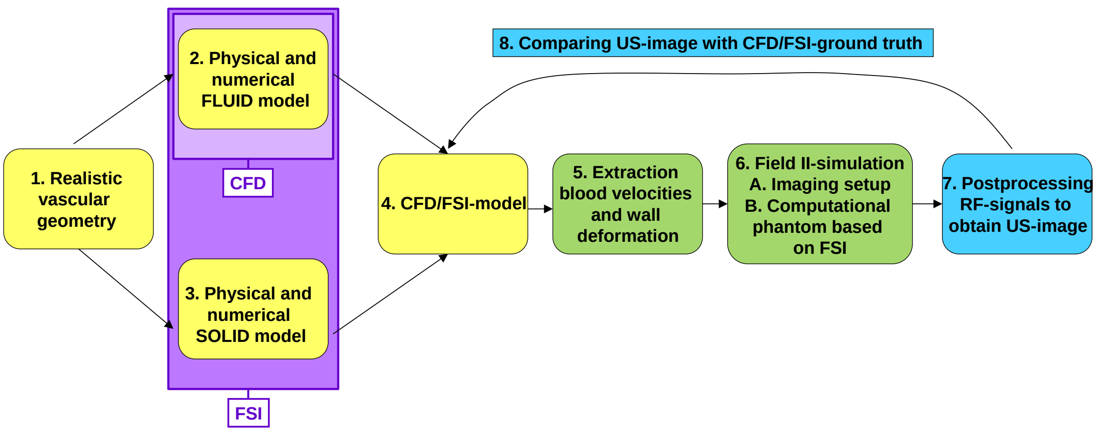

Figure 1: A flowchart illustrating the methodology of the ultrasound simulation environment

2.2 Rigid wall models

To couple the CFD-data to the positions of the point scatterers, 3D spatial interpolation of the CFD-velocities is executed in Matlab. Further, due to the large disparity in time scales between CFD (order ms) and US simulations (e.g. 0.067 ms for a frequency of the pulse excitations of 15 kHz), temporal interpolation of the CFD-velocities is necessary.

2.3 Distensible wall models

When integrating FSI and Field II, both the scatterer phantom of the blood pool and vessel wall require a more advanced approach. The fluid phantom in particular is highly challenging as straightforward interpolation techniques are no long applicable due to the changing fluid volume and the FSI-grid formulation (Arbitrary Lagrangian Eulerian method to match grid formulations for fluid and solid domain). Therefore, the scatterer displacement is approximated by updating scatterer velocities each FSI-timestep. To avoid that scatterers are displaced outside the fluid domain in a shrinking geometry or that voids are created in an expanding geometry, scatterers are displaced using the velocity vector from the subsequent FSI timestep, with the velocity vector extracted from an approximated mapped position at that timestep. This approach is justified due to the Backward Euler time discretization used by the flow solver. It provides correct displacements for scatterers at the fluid-structure interface, but it is an approximated approach within the flow field (cfr. fig.2).

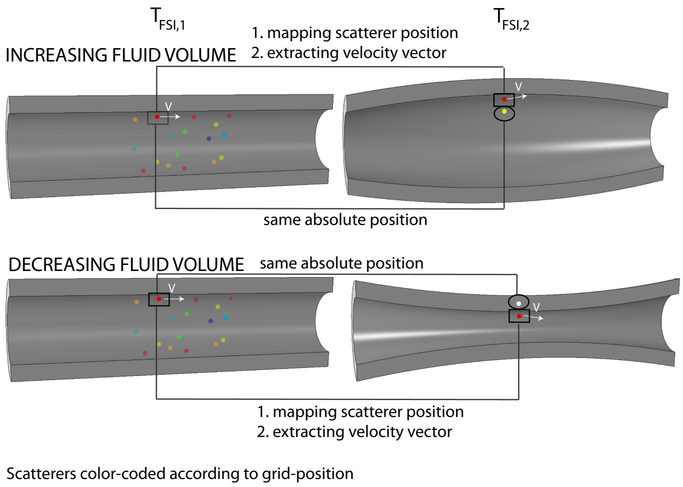

Figure 2: Principles behind the generation of the fluid phantom based on FSI-simulations

The structure phantom generation is less complex because the grid displacement corresponds with the material displacement and hence also with the scatterer displacement. However, the vessel wall needs more refined scatterer generation due to its complex composition, with flexibility of defining different scattering properties in different vessel regions. Besides these random scatterers, specular reflections at the transition regions between different tissue types (i.e. tissue/vessel wall and vessel wall/blood) are mimicked by placing scatterers at fixed distances along these interfaces.

2.4 Applications

Both with the distensible and rigid wall model, a commonly applied 1D blood flow estimator was investigated, i.e. color flow imaging (CFI). Panel A of fig.3 shows the comparison between CFI in the carotid artery during systolic deceleration and the true flow field known from CFD. Note that the CFD-data take into account the exact timing and positioning of the US-scanning sequence. It can be seen that CFI has difficulties capturing complex flow patterns. Panel B shows a color M-mode image (color-coded velocities along a scanline during cardiac cycle) resulting from blood flow in a straight tube, representative of the common carotid artery. For this case, the US-simulations were based on FSI-data, as can be seen in the fluctuating blood flow domain (panel B).

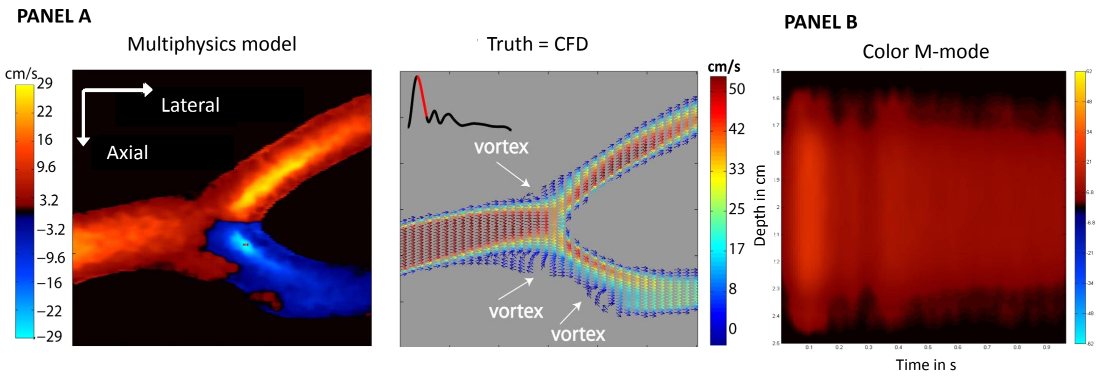

Figure 3: Panel A: comparison between color flow imaging and true flow field known from CFD. Panel B: Color M-mode image based on FSI-simulations in common carotid artery.

3 CONCLUSIONS

Coupling computational biomechanics and US-simulations provides realistic RF-signals from both tissue and blood which can be processed into US- images and measurements. Note, however, that simulations cannot include all the physical phenomena involved in the image formation process. Still, this simulation environment allows validation towards a gold standard, which is not possible for in-vitro or in-vivo testing, and as such this simulation tool has an important complimentary role to in-vitro/in-vivo validation.

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